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JOHN F. KENNEDY SPACE CENTER
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ROCKET-TRIGGERED LIGHTNING STRIKES AND FOREST FIRE IGNITION

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Abstract

The report presents background information on the rocket-triggered lightning project at Kennedy Space Center (KSC), a summary of the forecasting problem there, the facilities and equipment available for undertaking field experiments at KSC, previous research activity performed, a description of the atmospheric science field laboratory near Mosquito Lagoon on the KSC complex, methods of data acquisition, and present results. New sources of data for the 1990 field experiment include measuring the electric field in the lower few thousand feet of the atmosphere by suspending field measuring devices below a tethered balloon, and measuring the electric field intensity in clouds and in the atmosphere with aircraft. The latter program began in July of 1990. The report also lists future prospects for both triggered lightning and forest fire research at KSC.

Summary

Kennedy Space Center (KSC) is the center for and its operations the focus of the world's most exacting single-point, short-range weather forecasting problems. Thunderstorms, with lightning, hail, strong winds, and possibly tornadoes, represent the greatest hazard at KSC.

The present Atmospheric Science Research Laboratory program at KSC includes ground and airborne electric field measuring instruments (field mills); a ground-based radar; numerical models; rocket triggered lightning experiments; and conventional, fairly dense network of reporting stations and rain gages. When available, KSC will add a high-resolution wind profiler now being developed at Marshall Space Flight Center.

KSC recognizes the critical nature of smaller scale weather phenomenon in the forecasting problem addressed, i.e. short-period, precise, local weather forecasts. No other group has ever attempted to forecast on a routine basis the weather events KSC desires to predict. KSC will first attempt to improve the general understanding of smaller scale weather phenomena. The research project coordinates actions of disparate groups in collecting and analyzing heterogeneous data, and in integrating results into a real-time data display system.

Some significant problem areas: Most of the individual research efforts take place without adequate coordination with either KSC or the other cooperating groups, diluting the effort and rendering it ineffective. KSC must force the research program into a unified effort, demanding top KSC management support, which the program does not now enjoy. Devising a reliable operational forecasting method may take many years and considerable effort from KSC, other government weather-forecasting units, and academia.

Work on lightning-kindled forest fires began at KSC last year, at my initiation, and will continue.

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I

INTRODUCTION

1.1 BACKGROUND INFORMATION

The goal of the rocket-triggered lightning program (RTLTP) at Kennedy Space Center (KSC) is to permit more flexibility in the launch criteria, which, as will be mentioned shortly, currently restricts launch operations greatly. Better lightning forecasting would allow more launches without any higher risk to personnel or equipment. However, better forecasts require better knowledge and understanding of the phenomena itself, and that is the object of the rocket-triggered lightning field experiments at KSC.

The lightning program at KSC began in the 1960's, when the National Aeronautics and Space Administration (NASA) began building taller structures on the Center. Lightning strikes to Apollo 12 and, more recently, to an Atlas-Centaur rocket (in 1987), resulting in destruction of both the rocket and its payload, gave rise to added research to understand lightning better. KSC used their own employees, as well as cooperated with academic institutions and private companies in developing its lightning program. The present program includes ground and airborne electric field measuring instruments (field mills), radar, numerical models, rocket triggered lightning experiments, and conventional mesometeorological network of reporting stations and raingages.

The present launch criteria at KSC is very conservative as far as lightning potential is concerned, primarily because of our inadequate knowledge of the following factors: (1) How and under what conditions will aerospace vehicles trigger lightning in electrified clouds; (2) What distance lightning can travel from source to strike object (the aerospace vehicle); and (3) The location and extent of charge sources within clouds for natural and triggered lightning. Using lightning simulators and triggering lightning with small sounding rockets can help us determine the vulnerability of facilities and flight vehicles to the effects of direct and indirect lightning strikes.

Most of the individual research efforts by the various participating groups take place without coordination with either KSC or the other cooperating groups. KSC needs to integrate the entire research program into a unified program. Moreover, KSC needs to use the results and techniques developed for its day-to-day operations. Additionally, the limited meteorological expertise at KSC has hampered the research effort, requiring KSC to rely heavily on outside personnel and equipment for this research.

Numerous disparate groups and organizations have some expertise in various aspects of thunderstorm and lightning phenomena. Railroads know about lightning's ability to travel long distances along rail tracks, and to cause damage far from the original strike. Electric power companies also know how lightning travels through its conductors to damage equipment far from the thunderstorm producing the lightning. They also know lightning can couple into lines not originally struck by lightning. Airlines and the military know

lightning strikes aircraft both in the air and on the ground, and that aircraft can trigger lightning flashes even far from a thunderstorm cloud. Radio and television stations, as well as telephone companies know lightning can strike their towers and disrupt their transmissions and communications. It also couples into their equipment. Boaters, anglers, and golfers, among many others, know their recreational equipment (rods, masts, golf clubs) may serve as conductors for lightning strikes--particularly newer graphite materials in rods, masts, and club shafts.

1.2 THE LIGHTNING FORECASTING PROBLEM AT KENNEDY SPACE CENTER

KSC is the center for and its operations the focus of the world's most critical single-point, short-range weather forecasting problems. Many operations at KSC are extremely vulnerable to weather, usually in such novel ways that the forecasting problem has no counterpart in any other realm. The forecaster must develop their own experience at KSC, they cannot rely on any experience gained elsewhere to help them with unique KSC forecasting problems.

The special nature of weather at KSC, as well as extremely high economic and human costs if KSC launches (and therefore missions) fail leads to very precise forecasting criteria with extremely little margin for error. KSC success or failure also impacts directly and significantly on national and international opinion of United States' space effort and expertise. KSC failures draw considerable national and international attention! Thunderstorms, with lightning, hail, strong winds, and possibly tornadoes, represent the greatest hazard at KSC.

In its approach to forecasting extreme weather, KSC recognizes the critical nature of smaller scale weather features and phenomenon (mesoscale components) on the problem addressed: short-period, precise, local weather forecasts. Even the excellent world-wide weather data available through MIDS cannot by itself make the local weather forecasting problem easier. KSC plans to integrate weather data from satellites, radar, its own local mesonet network of weather stations, regional weather stations, and data on local lightning strike into the forecasting technique. When available, KSC will add a high-resolution wind profiler (now being developed at NASA Marshall Space Flight Center [MSFC]).

Other data for the weather forecasting scheme envisioned include dual-doppler radar, NEXRAD at Melbourne, Florida; ground- and airborne electric field measurements from KSC-operated sites; and local lightning-locating data. If at all possible, KSC envisions using its rocket-triggered lightning data into an operational forecasting technique. Since no one, to our knowledge, has ever attempted to forecast on a routine basis the weather events KSC desires to predict, we can only describe the forecasting as experimental. Devising a reliable operational forecasting method may take many years and considerable effort from KSC, other government weather-forecasting units, and academia.

The approach KSC will take will first attempt to improve our understanding of smaller scale (mesoscale) weather phenomena. Only when we obtain an adequate

knowledge of the systems we wish to forecast can we confidently try to predict that phenomenon. This approach requires, however, the close coordination and cooperation of disparate, heterogeneous data, and its integration into a real-time (preferably interactive) data display system. The forecasting problem will also almost require such a technique, because KSC must forecast weather events lasting less than one minute, thus requiring almost instantaneous data collection and display. This requirement may not be unique (airports would also like to have this capability), but the economic and political costs of delays and wrong decisions at KSC are much, much higher than anywhere else.

1.3 RESEARCH PROJECTS AND RESEARCH FACILITIES AND EQUIPMENT

1.3.1 RESEARCH INVESTIGATORS AND THEIR PROJECTS. The rocket-triggered lightning research at KSC involves a number of different research groups from several institutes. They are also working on different, but complimentary, research projects.

The Centre d'Etudes Nucléaires de Grenoble (CENG), from Grenoble, France has two programs at KSC. Their work encompasses launching the rockets to trigger lightning as well as experimental study of the electrostatic fields required for aerospace vehicles to trigger lightning. These two projects will continue at a reduced level during 1990.

The CENG project to launch rockets to trigger lightning also has two parts. The first part is, obviously, to trigger lightning, thus bringing lightning strikes down the conductor trailing behind the rocket to a known location for further study. The second part is to launch instrumented rockets to obtain a fast vertical profile of the electrical fields existing in the atmosphere. The French use two types of rockets, one to reach heights of about 1 kilometer, the other, a Might Mouse rocket, to reach 7 km height. These rocket-derived electric field profiles are then verified by comparison with measurements taken by a series of field mills attached to the tether of an aerostat, as illustrated schematically in figure 1.1 on the following page. The goal of this second part of this project is to develop a method for taking accurate vertical electric field strength profiles in storm conditions, when the atmospheric electric fields fluctuate rapidly.

The second French project is to study the electrostatic fields that exist at the beginning and ending of electric storms, as the fields oscillate more at those times. The method is to launch a sounding rocket to measure the electric field profile, followed a few seconds later by a rocket designed to trigger a lightning strike. The second rocket trails a copper wire designed to represent the conductive body and charged exhaust gasses of the aerospace vehicle it simulates. The experiments compare theoretical concepts with the results of rocket-borne and ground-based magnetic and electric fields, strike current, and flash luminosity. The object is to understand and then ultimately to predict the triggered lightning process, which will allow KSC to develop more accurate warning criteria and measuring techniques. A further objective is to measure lightning strike waveforms in order to allow more

accurate simulation of lightning strikes. This will let personnel test the vulnerability of vehicles and associated equipment and facilities prior to their use.

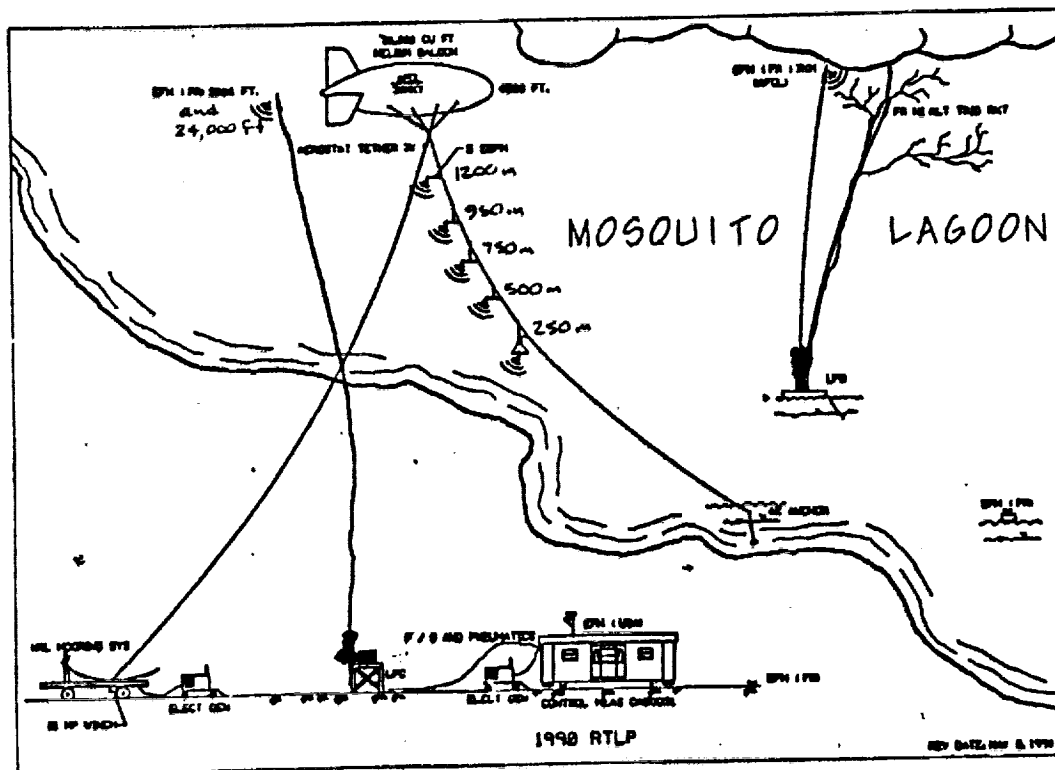


Figure 1-1: The 1990 Rocket Triggered Lightning Project schematic identifying equipment and showing their relative location to each other. (For location of the RTLP, refer to **figure 1-2.**)

Sandia National Laboratories will test the response of aerospace structural materials such as aluminum, titanium, and copper to direct lightning strikes, both natural and triggered. As with part of the French project, the results will also be used to characterize the waveform of lightning strikes for simulations purposes. This project, because it intends to characterize natural as well as triggered lightning, will use a portable launch system for triggered lightning.

Massachusetts Institute of Technology will use microwave radar to measure the plasma temperature of the lightning channel for the triggered lightning strokes. This projects aims at improving our knowledge of the thermodynamics and energetics of lightning discharge.

Embry-Riddle Aeronautical University and the University of Mississippi plan to collaborate on a balloon-tethered field mill experiment above vegetation. This program hopes to understand the shielding effect of low-level space charge produced by corona discharge from the vegetation, which will help interpret ground-based field measurements in relation to fields aloft. This group will compare their measurements with those of the French and the airborne field mill measurements by the Air Force.

Other groups will analyse streak camera images of lightning strikes to help in defining the structure of the strike channel, and measure the ozone and nitrogen produced by the strikes.

1.3.2 THE ATMOSPHERIC SCIENCE FIELD LABORATORY (ASFL) FACILITIES AND EQUIPMENT. Kennedy Space Center (KSC) lies in a region of the United States with one of the highest frequencies of thunderstorms and lightning activity. Figure 1-2 shows the location of the ASFL and some other sites used for the Rocket-Triggered Lightning Project (RTLTP). UCS 10 and UCS 11 refer to the location of unmanned camera sites used to record launches. The headquarters building (HQ Bldg) and launch complex 47 (CX 47) are also shown.

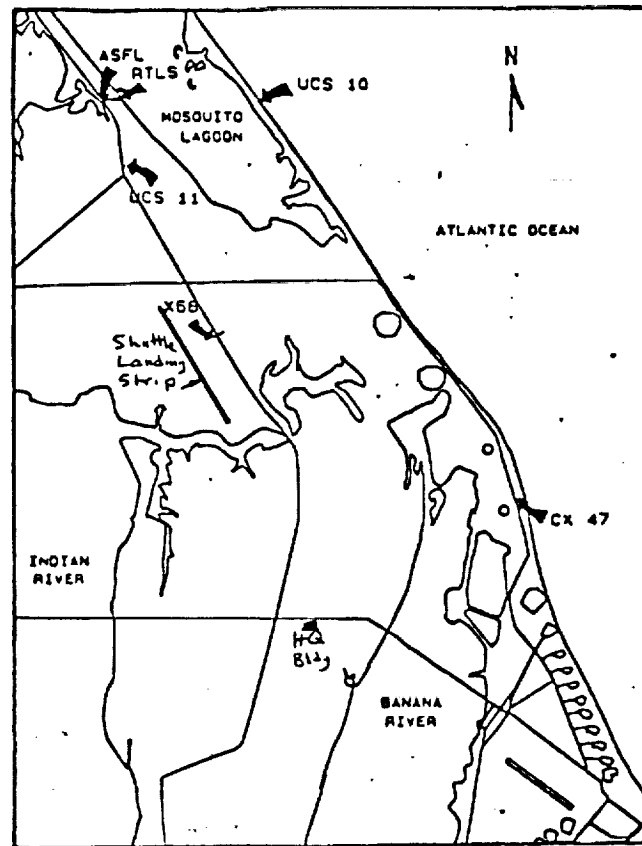


Figure 1-2: Selected site locations used for the 1990 Rocket-Triggered Lightning Project and their relation to other points on Kennedy Space Center.

KSC operations involve some very expensive equipment (the Shuttle, satellites, and launch vehicles) subject to critical and exacting time schedules. At the same time, launch support equipment such as towers, antennae, above ground and buried cable, are subject to damage or interruption of their function and use from lightning strikes. This combination of conditions make lightning both a hazard to and a significant factor in success or failure of KSC operations. As a result, KSC has been involved in and conducted extensive lightning studies for more than two decades. These studies involved characterizing lightning flashes, devising methods of protecting equipment from lightning strikes, and ways to locate and predict lightning and thunderstorms. Since the early 1980's, KSC, in conjunction with other Government organizations, private companies, and universities, has intensified its studies of thunderstorm and lightning phenomena.

KSC and the Eastern Space Missile Center (ESMC) weather group delve into thunderstorm and lightning forecasting, as well as devising methods of predicting other significant, adverse, or severe weather events (e.g. freezing precipitation, fog, icing, or strong or gusty winds). The combination of KSC and ESMC have developed one of the finest facilities for forecasting short-range weather events. The KSC/ESMC facilities include weather satellite and radar data, a mesoscale weather observation network (more than fifty stations), and the Meteorological Interactive Data Display System (MIDDS) which supplies world-wide meteorological data and soundings. The KSC also uses a tethered balloon for research on thunderstorms and lightning, and may be able to include this in future forecasting techniques.

KSC and ESMC wish to create and operate an advanced weather support and forecasting system in order to reduce the weather-related hindrances to KSC operations. The KSC program also plans to transfer to other weather forecasting units (such as the US Air Force or the National Weather Service) the technology and knowledge gained through this research.

The Federal Aviation Administration (FAA), Air Force Wright Aeronautical Laboratories (AFWAL), and the US Naval Research Laboratory (NRL) are among the Government groups interested in lightning studies at KSC. KSC and other groups are interested in (1) characterization of lightning hazards to KSC operations, to communications, to power distribution, and to command and control systems; (2) remote lightning detection; and (3) understanding the "advent and demise" of thunderstorms. In addition, certain groups within the Government are interested in using lightning strikes to simulate the electromagnetic pulse (EMP) nuclear weapon bursts might send out.

After learning more about lightning and its effects on air- and spacecraft, KSC would like to transfer the techniques and knowledge gained from its studies to operational forecasting and to academic institutions training weather forecasters. This should ensure qualified forecasters for future operations.

1.4 DATA ACQUISITION

Items investigated in KSC lightning and thunderstorm studies include static and field charges using electric field measurements in and around KSC; locating and counting lightning discharges (cloud-to-ground strikes, mainly) within 200 miles of KSC; radar data from the KSC region; surface wind data using a mesoscale network of measuring stations within about 50 miles of KSC; electric and magnetic fields and lightning current measurements from the KSC area; and other meteorological data obtained from local, regional, and national sources. These data will, hopefully, be integrated into a forecasting method and applied to improving short-term weather forecasting and verification of numerical weather forecasting, and to evaluating lightning warning procedures.

The Maxwell current and its changes with time may help researchers understand when thunderstorms begin ("turn on") and when they quit ("turn off"). Maxwell current may thus ultimately lead to an approximate threshold for impending lightning strikes. (Lightning and its accompanying thunder define a thunderstorm; without these two phenomena, the event is merely a rain- or hailshower.)

Photo analysis of lightning may be used to quantify several parameters, such as size and shape of strokes. Streak images yield stroke propagation speed. Photography on calibrated film can determine flash luminosity. If luminosity is a function of current, then we can measure lightning current directly. Further, time resolved lightning spectra would then yield electron temperature in the lightning channel. Photographic images can be analyzed by video densitometers, if digitized, or conventional densitometers if not.

The program at KSC is the first program to measure all parameters (electric and magnetic field, current, electron temperature in the lightning plasma, luminosity, spatial orientation, and stroke propagation speed) at the same time, thus allowing case studies to test theoretical and numerical models of lightning behavior.

Kennedy Space Center (KSC) receives wind, temperature, and humidity observations from a network of over 50 instrumented towers covering an area about 53 by 57 km (about 1600 square kilometers) as shown in Watson *et al.* (1987). Most wind instruments have been mounted on top of standard 54-foot tall telephone poles, and set to record wind data at five-minute intervals. When in use during the RTLP, data from this network is recorded on computer tape and used in mesoanalyses of thunderstorm and lightning case studies.

A network of five direction-finding stations around KSC locate negative lightning flashes (where earth is positive relative to cloud). A paper by Lopez and Holle (1986) describe this lightning direction-finding method.

A United States Air Force WSR-74C radar located at Patrick AFB, approximately 30 km SSE of KSC, supplies data at five-minute intervals. A Weather Bureau radar at Daytona Beach, about 100 km NNW of KSC, also supplies radar imagery at irregular intervals. The Lightning Location and Protection, Inc, (LLP)

Integrated Storm Information System (ISIS), which records negative lightning flash information as well as Daytona Beach radar information, is out of operation for the 1990 RTLP season. When it operates, this ISIS equipment is located at the Range Control building on Cape Canaveral Air Force Station. Until it returns to service, the national lightning location system, operated this year by Sandia National Laboratories, provides similar data.

Lightning triggered when small rockets trailing a conductive wire behind them (rocket-triggered lightning, RTL) are launched near active thunderstorms provide several advantages for scientific study of lightning. First, lightning occurs at a pre-defined place and at a pre-determined time. This allows the researchers to measure parameters seldom--and then only with extreme difficulty--measured in the natural atmosphere. Secondly, it allows a detailed look at the very long "leader" strikes propagating into un-ionized air, close to the conditions prevailing in an unmodified environment. Both of these advantages help researchers understanding lightning leaders, thus understand lightning itself better--and, more importantly, that triggered by aerospace vehicles traversing that region of the atmosphere.

Suspending an isolated metallic object (a cylinder about eight feet long and two feet in diameter) below a tethered balloon as a lightning strike object (LSO) may also simulate an aerospace vehicle-triggered lightning (ATL) object. Lightning flash leaders observed and measured during such strikes will provide data for comparison with prior observations, hopefully to verify or refute the bi-directional ATL model commonly proposed. The series of field mills suspended along the tether cable provides electric field measurements around the LSO. This experimental set-up also allows negative leader current to be measured at the LSO site, possibly permitting return-stroke current measurements at ground and higher levels at the same time. Streak cameras and conventional photography record visual imagery for later quantitative study.

Data taken both over land and over water allows similarities and differences to be observed and measured. Rocket launches over water represent a "purer" electric lightning signature, since there is no distortion of the signal from the ground or support equipment around the launch pad. The 1990 RTLP includes launches from land and water RTLs; my proposal is to launch from each site alternately, or from each at short intervals, i.e. quasi-simultaneously.

Other sensors include microphones to record the sound of thunder, to complement the photo-recorded lightning flashes; and current sensors in the ground, which are correlated with negative cloud-ground potential.

II

PRESENT RESULTS

2.1 UNIQUE METHODS OF DATA ACQUISITION

The 1990 rocket-triggered lightning strike research season envisions recording positive lightning strike data as well as negative, using a system developed by the State University of New York at Albany (SUNYA). The SUNYA system uses satellite data to provide actual lightning strike location data. Simultaneously, rockets carrying special electric field measuring instruments ("field mills") will be launched to obtain electric field strength data up to 7000m altitude.

KSC will also suspend field mills at intervals along a cable attached to a tethered balloon located near the rocket launch site. This will supply a vertical sounding of electric field strength near the triggering site, important data presently missing. From four to six field mills located along the tethering cable will supply field strength at heights up to approximately 1200 m above the ground. This arrangement is shown in **figure 1-1** on a previous page, but repeated here as **figure 2-1** for the reader's convenience.

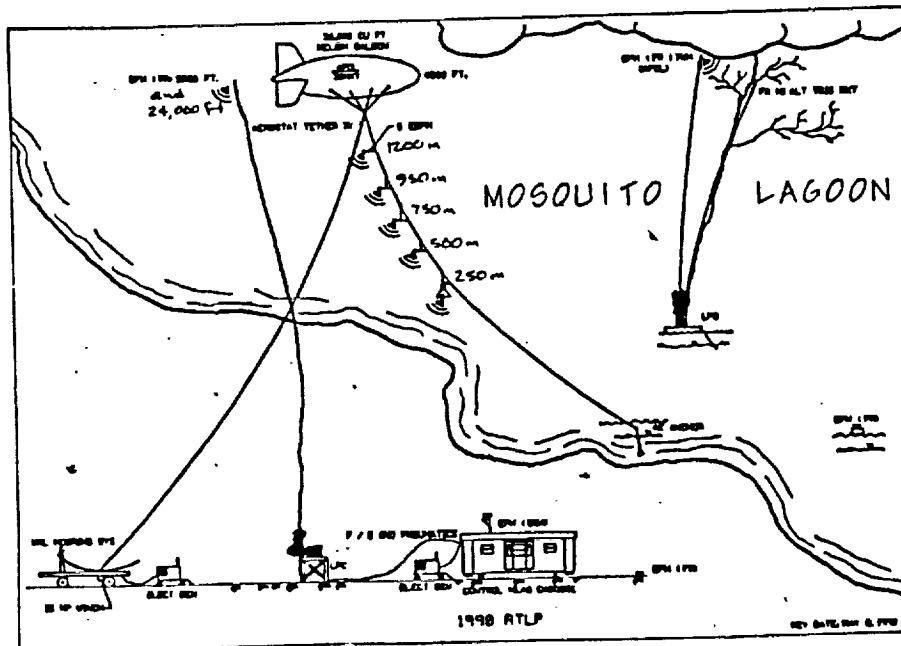


Figure 2-1: The 1990 Rocket Triggered Lightning Site schematic identifying equipment and showing their relative location to each other. (For location of the RTLP, refer back to **figure 1-2**.)

2.2 RESULTS FROM 1990 FIELD EXPERIMENT

2.2.1 PROBLEMS WITH EQUIPMENT. Prior to beginning the 1990 field experiment at the Rocket-Triggered Launch Site (RTLIS), KSC had to revise the operating procedures. This delayed the field experiments; consequently, the program had gathered little lightning strike or fire initiation data prior to my departure. This report thus presents results of preliminary case studies for 5 June and 3 July 1990, which I undertook during July.

Another problem, as in 1989, concerned the lightning strike display system, ISIS, which quit functioning entirely in 1990. The ISIS should record both lightning strike location and radar return, and is used both to deduce the physical relationship between the lightning strike and the parent thunderstorm, and to locate sites of fire initiation. Likewise, as in 1989, the French contingent from Grenoble delayed their arrival by about ten days. Since they actually run the RTLIS, launch the triggering rockets, and gather data, their delay pushed the start of operational rocket launches back still more.

All RTLP equipment and personnel appeared to be ready for the first rocket launch only on July 31st. Unfortunately, for a number of days thereafter, weather conditions did not produce lightning at the launch site on Mosquito Lagoon.

2.2.2 PROBLEMS WITH COORDINATION AND COOPERATION. With nearly a dozen groups cooperating in the lightning project, occasional lack of coordination seem inevitable. In my view, this need not happen at all. Every group should have been adequately informed of their role in the project and how they were to support every other group. Unfortunately, this certainly did not happen in the case of the Cape Canaveral Air Force Base weather station and its personnel. I called them a number of times between July 6th and July 31st, requesting data for the storm development on the afternoon of July 3rd. To their credit, they sent me data for 1200 July 3rd (figure 2-5), but never for 0000 July 4th, a time closer to actual storm development around 2000. On each occasion of telephoning the weather station, I seemed to talk to someone new, who did not know anything about my previous requests. The two civilian employees promised to take care of my request (handling such requests apparently is part of their job), but they failed to do so. One apparently became ill, the other apparently merely did not do the job. Finally, after at least a dozen telephone calls, I was informed on August 1st that the weather station only keeps plotted charts and maps for two weeks, and the data for July 4th had been destroyed. As a result, I cannot include this information in this report.

KSC should improve its coordination with support units such as the weather station to improve cooperation in the RTLP.

2.2.3 USING A "STORMSCOPE" TO LOCATE NEW THUNDERSTORM CELL DEVELOPMENT. Bill Jafferis asked me to study the feasibility of using the commercially available Stormscope as an initial indicator of lightning. The idea of using a

Stormscope as a preliminary indicator of thunderstorm activity has merit: Sites without access to the more elaborate lightning detector data or radar could, with help of the Stormscope, get a general indication of lightning activity and direction, even if the Stormscope does not indicate distance to the flash accurately. Further, the Stormscope is relatively inexpensive, has been used in aircraft for many years, and indicates both positively and negatively charged lightning strokes.

As requested, I studied Stormscope displays and compared them with radar returns and the ISIS lightning indicating system. KSC personnel had recorded displays of all instruments and equipment on June 5th, and I looked at all three displays taken from those videotapes. My study confirmed the impression that the Stormscope indicated direction to lightning activity, but the distance was not accurate. As a result, I concluded that a Stormscope located at selected sites would be a good alternative to installing expensive equipment, or running electrical cables to those sites in an effort to remote the data from other locations to these users. Moreover, since Stormscopes display both positive and negative lightning discharges, they can pick up developing and newly developed storms better than the ISIS. This makes the Stormscope a good, reasonably priced, readily available system for use in locating new thunderstorm activity.

2.2.4 SOME PRELIMINARY RESULTS FROM THE 1990 FIELD EXPERIMENT. Due to delays outlined above, coupled with my departure August 7th, this report gives only a few preliminary results from the 1990 field experiment. As noted above, I studied the storm development occurring on 5 June and 3 July 1990, as some interesting new storms developed on those days.

From July 10th through at least August 6th (and possibly continuing for at least another two weeks after my departure), KSC hosted multi-party airborne field mill flights almost daily. During these nearly two dozen flights, Air Force and other parties measured the electric field at various altitudes, both in and out of stratus, cirrus, and cumulus cloud, and correlated them with surface and tethered field mill measurements. The purpose was to be able to extrapolate field mill measurements taken during operational RTLP launches to higher altitudes, i.e. to be able to extend the electric field readings taken from tethered field mills and those measured by small rockets (attaining heights of about 7000m) to the top of the thunderstorm cloud, which often attain altitudes of at least 15,000m. The aircraft measured typically 1kV/m to 2kV/m outside clouds, and also inside stratus or dissipating cumulus clouds. The instruments also recorded up to 60kV/m inside active cumulus and cumulonimbus clouds, and generally noted turbulence, precipitation, and often icing along with higher field strengths. As of August 1st, no operational rocket launches have verified these findings.

Figures 2-2, 2-3, and 2-4 show, respectively, an interesting satellite image, the corresponding radar return, and two soundings for June 5th, 1990. As all the imagery, (satellite, radar, and lightning location) were taken as single frames from videotape of the monitor displays, the reproduction quality is

poor, and I have not included all of the satellite or radar data, nor any of the lightning strike data, in this report. For those who might have an interest, original images are available from Bill Jafferis, DL-ESS-22, HQ Building, Kennedy Space Center, FL 32899.

Figure 2-2 shows GOES 7 satellite imagery from 2031 UT, June 5, 1990. It indicates the arch of clouds (denoted by "A") formed by the downdraft outflow from dissipating thunderstorm "B" forcing moist air to rise. New cell development ("C") on this arch may be the result of interaction between the outflow from "B" and thunderstorm "C," since that thunderstorm cell appeared (from previous imagery not shown here) to be expanding towards the south. New cells "D" and "E" forming upwind of dissipating thunderstorm "F" appear to be developing along a mesoscale boundary between moist and drier low-level air. This apparent boundary is marked by a wedge-shaped region of cumulus clouds extending from the eastern edge of Tampa Bay to cell "F" on the eastern coast of Florida. The overshooting tops on thunderstorm cells "D" and "E," indicating strong updrafts and rapid cloud development, are not apparent in this imagery, but enlargements reveal them. The well developed sea breeze along the eastern coast of Florida shows up as a line of clouds (marked "G") just inland of the coast.

Figure 2-3 shows the radar returns for 2029 universal time (UT), two minutes prior to figure 2-2. Thunderstorm cells "D," "E," and "F" can be clearly seen, as well as another storm cell north of "E." This radar echo apparently corresponds to a feature hidden by anvil debris in figure 2-2. Other thunderstorm cells visible in satellite imagery are beyond the 60n.mi. radar range selected in this example.

Figure 2-4 shows two soundings (taken at 1015 and 1205 UT) plotted on the same Skew T-Log P diagram the U.S. Air Force normally uses. Lines of equal temperature slope up to the right ("skew-T"), while the logarithm of atmospheric pressure decreases upward ("log-P"). The temperature trace is the solid irregular curve, and the dew point temperature is the dashed irregular curve. Lines of equal moisture, not labeled, appear as dashed straight lines sloping up to the right somewhat more steeply than temperature lines. The solid lines which appear to converge as they slope up to the left denote the change in temperature with pressure dry air ascending adiabatically in the atmosphere would experience, while the four dashed lines curving up to the left denote the temperature change with pressure that rising saturated air would experience. Together with the temperature and dew point traces, these sets of lines can be used to evaluate static stability of the atmosphere, potential for thunderstorm formation, and estimated thunderstorm cell height. The final items depicted are short barbs indicating wind direction and speed, plotted along the right margin. The length of the line segment indicates relative wind speed (the actual value is given to its right, in knots), and the orientation of the line indicates compass direction clockwise from true north. Most wind directions lie between southwest and northwest in this case.

Figures 2-5 and 2-6 show weather facsimile products for July 3rd, 1990. Due to the poor quality of other images available, and lack of data for other times, I have not included any in this report.

Figure 2.5 shows the weather analyses for the 200 (A), 500 (B), 700 (C), and 850mbar (D) levels for 12:00 UT, July 3, 1990. Light lines in each map denote height contours on the pressure surface, which correspond to lines of constant pressure (isobars) on a surface analysis. Centers of high height contours are marked "H," those of lower contours "L." The heavy curves emanating out from low centers depict troughs, while heavy wavy lines from highs denote ridges. Isotherms are dashed. The jet stream is shaded on the 200mbar map.

Figure 2-6 shows a locally produced surface weather map for 12:00 UT, July 3, 1990. A low pressure center lies along the eastern Florida coast, midway between Miami and KSC at this time. The troughs (marked "Trof") radiating outward from this low pressure center induced convergence, which, when combined with the sea-breeze convergence later in the day, gave rise to thunderstorm development. The outflow from one of these storms forced new storm cell development ahead of the original storm. This new thunderstorm passed over Titusville, producing considerable lightning and rain. (The data, charts, and maps for this case cannot be shown or included in this report, because the original data was not recorded, and the maps were destroyed, as noted previously. However, I noted the development with my own eyes, as I was physically present in the Technology Transfer Unit (TTU) on that afternoon and watched this storm develop on radar and through satellite imagery and the convergence indicated by the mesoscale wind network around KSC.)

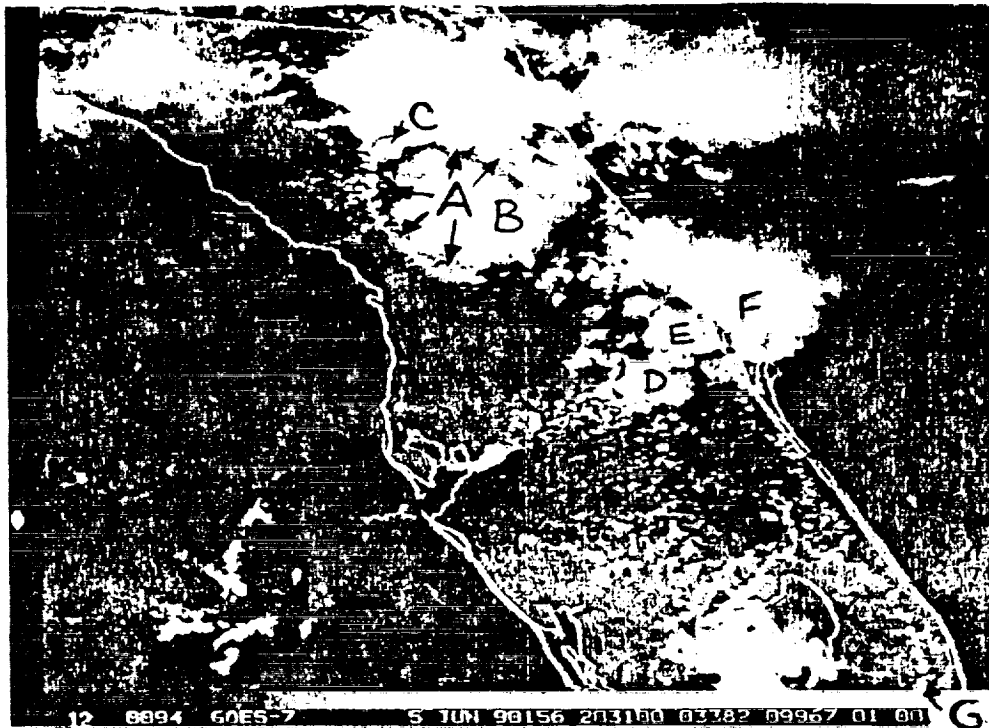
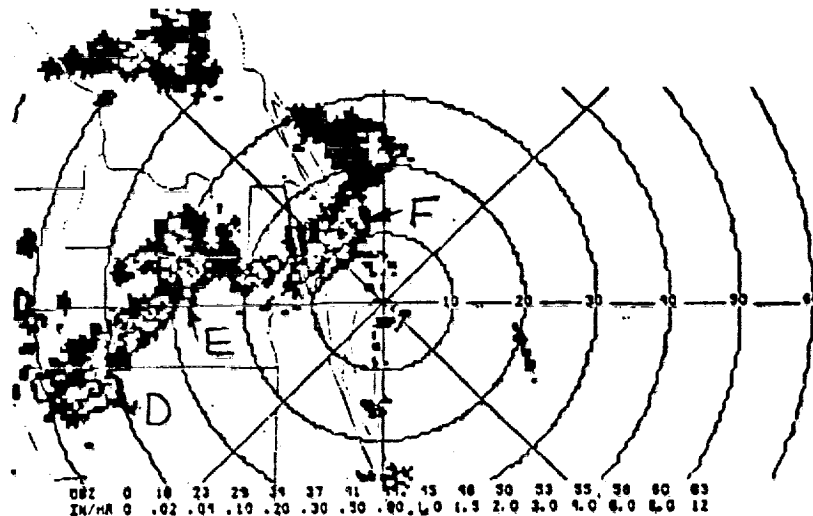


Figure 2-2: GOES 7 satellite imagery from 2031 UT, June 5, 1990, showing the outflow arch (A) from a dissipating thunderstorm (B), new cell development (C) on this arch, and new cells (D) and (E) forming on the upwind side of storm (F), along a mesoscale boundary between moist and drier low-level air.



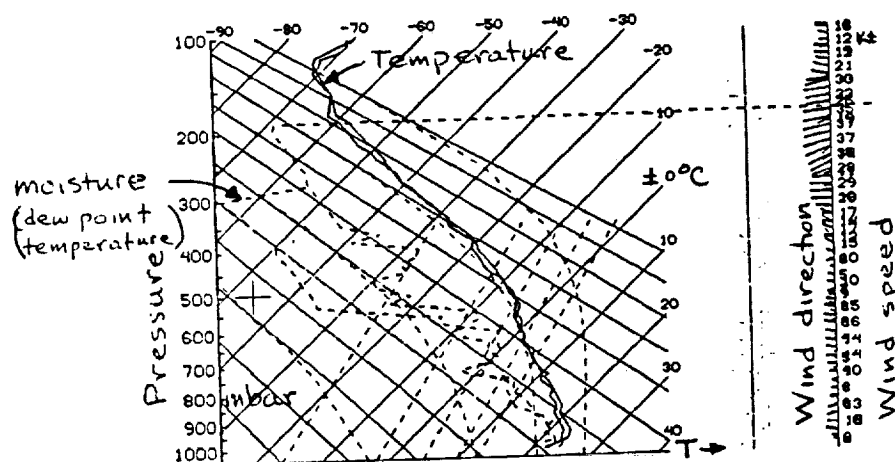


Figure 2-4: Temperature, moisture, and wind soundings for Kennedy Space Center for 1015 and 1205 UT, June 5, 1990. The two soundings have been inadvertently plotted on top of each other.

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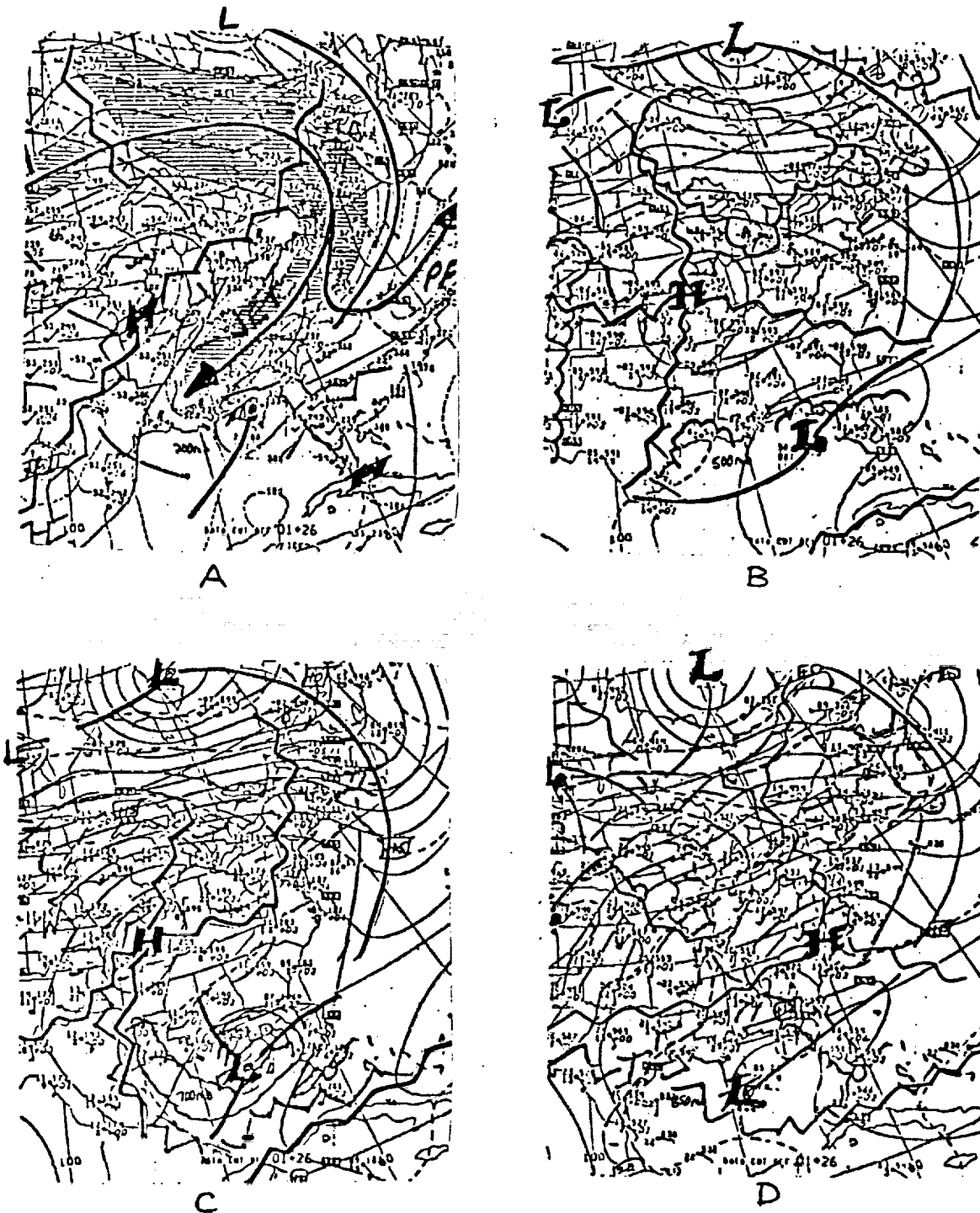


Figure 2.5: Analyses of 200 (A), 500 (B), 700 (C), and 850mb (D) levels for 12:00 UT, July 3, 1990. Light lines denote contours of height of the pressure surface; heavy curves depict trough, while heavy wavy lines denote ridges. Centers of high height contours are marked "H," those of lower contours "L." Isotherms are dashed. The jet stream is shaded on the 200mb map.

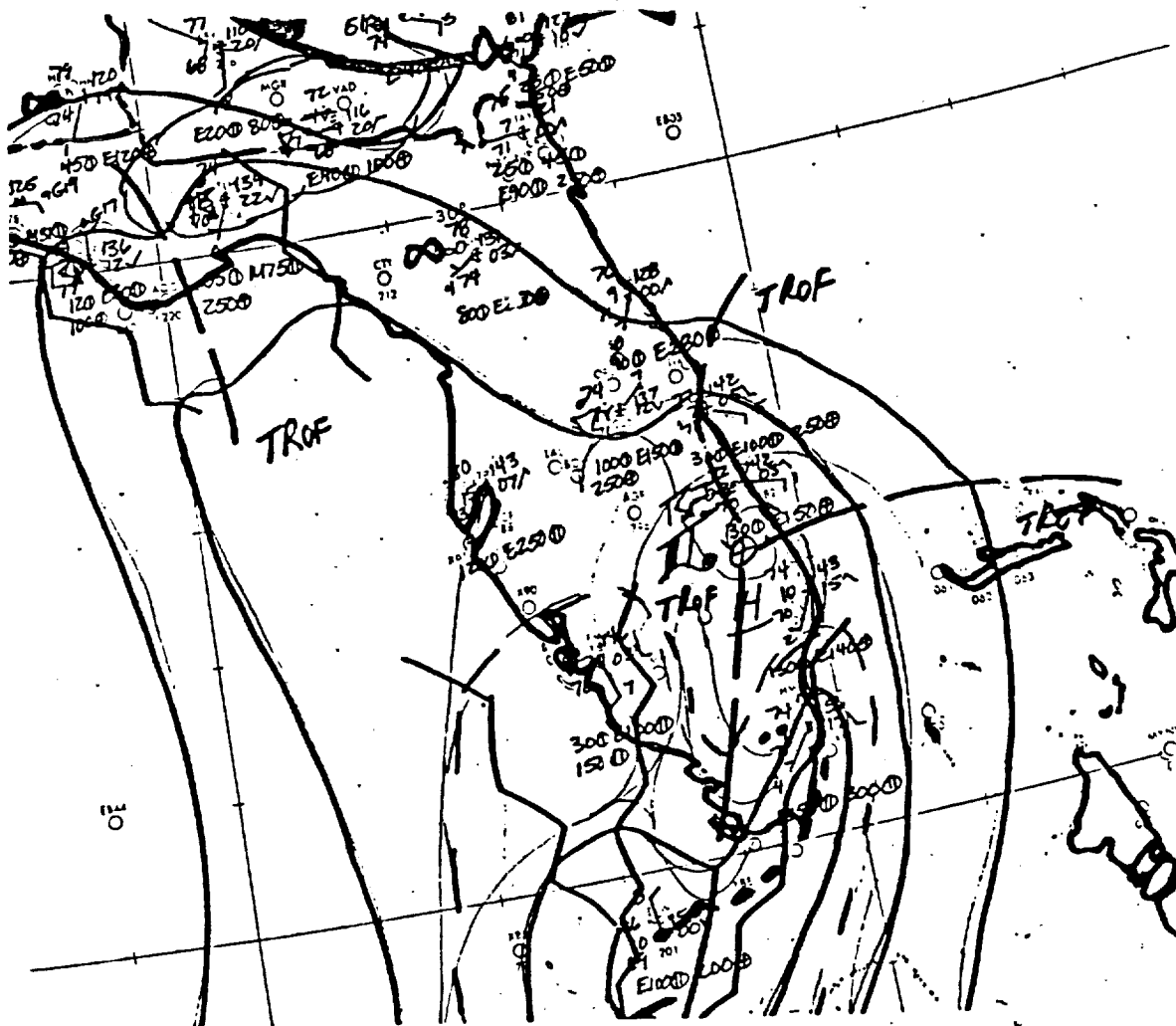


Figure 2-6: Locally produced surface weather map for 12:00 UT, July 3, 1990. A low pressure center lies along the eastern Florida coast, mid-way between Miami and KSC at this time. The troughs ("Trof") radiating outward from this low pressure center induced convergence, which, when combined with the sea-breeze convergence later in the day, gave rise to thunderstorm development near Titusville about 19:00 UT.

2.3 LIGHTNING-KINDLED FIRES IN FOREST PRODUCTS

The plan was to place piles of toothpicks, 1/4-inch, 1/2-inch, and 1-inch wood dowels; kindling sawn from 1/4-inch plywood, 1-by-1's, and 2-by-2's; and ultimately actual examples of local plants collected with the help and permission of the Fish and Wildlife Service at the launch site to see which ones ignite. KSC also intends to measure the current in each strike. The idea of using well defined sizes of wood is to achieve reproducible results. Again, no results have been obtained due to paucity of triggered lightning.

Kennedy Space Center personnel involved in the lightning project are to lay this kindling near the launch site and record the results. They are to forward the data to me for my analysis and interpretation.

III

CONCLUDING REMARKS

3.1 NEW DEVELOPMENTS AND PROPOSED METHODS FOR FORECASTING LIGHTNING

The current system for forecasting thunderstorm location and lightning strike location uses a composite technique including maximum radar reflectivity of thunderstorm cells; rate of change in radar reflectivity; gradient of radar reflectivity; location, number, and frequency of negative lightning strikes; surface wind convergence; and surface wind pattern. (Surface wind pattern typically varies with stage of thunderstorm development. See Byers and Braham [1949] or Watson et al. [1989])

As Shuttle and other launches become scheduled more frequently, KSC operations become less tolerant of delays. Thus, KSC forecasters need to identify more low-risk launch window, requiring improved forecasting of weather events such as triggered lightning, wind shear, and turbulence with accuracy and timeliness unique to space programs. Measurements of electric fields, for example, have not yet been included in the forecasting process for triggered lightning. Moreover, many critical weather factors cannot even be measured directly; the forecasters infer their value from their relationship to other parameters they can measure.

Launch safety needs both accurate current weather data and forecasts for two hours or less. Observations limit the accuracy and quality of forecasts, particularly on this short-term forecasting, or nowcasting, time scale. KSC must improve its observations, including new instrumentation and measuring systems, to improve operational forecasts.

New instrumentation is no panacea, however. New instruments improve detection, not necessarily forecasting. Forecasting methods use the data available when those methods were developed. KSC needs to modify forecasting methods and techniques to include new data sources. Displays for lightning detection networks and new instruments to detect in-cloud and cloud-to-cloud lightning, for example, should be incorporated into KSC weather forecasting. Likewise, local weather analysis and forecasting techniques specific to KSC need to be developed. KSC should also develop an interactive, computer-aided weather decision-making system, and possibly numerical weather prediction models specific to KSC operations.

Local convergence of surface winds still induce thunderstorm formation at KSC. Byers and Rodebush (1948) and Byers and Braham (1949) suggested this cause, and many later experiments and studies supported them. The comparatively dense network of surface wind measurements at KSC allow use of local convergence for short-period forecasting. In particular, the forecaster must locate and follow the movements of the sea breeze, as it dominates all other convergence forces in and around KSC. A proposed, new prediction method (not yet completed) is to write computer programs to calculate and plot convergence over several sub-areas within the KSC research area (fig. 1-2), and to

locate lines and regions of convergence within the same area. Breaking the KSC research area down into four or nine smaller regions, or sub-areas, should be adequate. Watson and Blanchard (1984) noted that smaller areas provide reasonably good predictions of thunderstorm development using average convergence data, but Watson *et al.* (1989) noted that larger ones do not, since the averaging process dilutes the convergence (large on a small scale) when averaged over an area as large as the KSC research area. My proposal to break the KSC area down into smaller units for automatic convergence computation would solve the apparent dilution problem.

Surface convergence does not, of course, take into account any dynamic processes occurring higher in the atmosphere. The MIDDs provides upper-level information. By writing programs to analyze and plot various combinations of data (the best combinations have yet to be determined), the forecaster should be able to predict at least the potential for triggered lightning. One thing the previous research at KSC has shown: Lightning appears to begin just after maximum convergence (averaged over a fairly small area), to peak before average divergence over the same area reaches a maximum, and to decrease as divergence decreases.

3.2 FUTURE PROSPECTS AND RECOMMENDATIONS

From its start seven years ago on the shores of Merritt Island's Mosquito Lagoon, about eight miles north of KSC's Vehicle Assembly Building, NASA's Rocket-Triggered Lightning Program (RTLTP) has developed progressively into a formidable research effort. NASA's desire to improve KSC lightning protection and lightning forecasting gave the RTLTP emphasis. Each year adds new features to improve scientific knowledge. The RTLTP added a tethered balloon in 1988. In 1990, the French will be using two different rockets to measure electric fields up to about 7000m above the ground.

Other new elements added in 1990 included raising the height of the tethered balloon to about 1500m in order to measure the electric fields to greater height with the field mills suspended below the tethered balloon; aircraft flying into clouds at various altitudes to measure the electric fields inside and outside these clouds (the airborne field mill experiment); and attempts at quantifying lightning-initiated kindling of forest materials. Placing field mills at intervals between the ground and the height of the balloon provides data on change of atmospheric electric field strength with altitude, the better to help characterize the lightning strike potential over land and water. Field mills detect and help locate the lightning, as well as allow study of the electric field environment prior to lightning strikes. The series of field mills suspended below the tethered balloon provide a more complete view of weather conditions conducive to rocket- or aircraft-triggered lightning.

The future thrust should be in combining and assimilating the many diverse data sources into an integrated short-term predictive technique. One main thrust should lie in setting up an expert system or knowledge bank, a

"forecaster's helper" along the lines of the artificial-intelligence based "doctor's associate" used by some physicians and in some hospitals. A second main effort, writing programs to analyze the myriad data sources (KSC local wind fields, electric fields, radar, and other data from the Meteorological Interactive Data Display System [MIDDS] and the Digital Weather Image Processing System [D-WIPS]) automatically, should support development of an expert system. KSC apparently recognizes the fact that too little work has been done in integrating the excellent data sources available, because they are looking for help in this vital area. I plan to continue helping KSC in these areas.

Eventual civilian "spin-off" applications of RTLP results include aircraft lightning avoidance, and lightning protection systems to thwart electrical power and/or telecommunication outages.

To undertake the Rocket Triggered Lightning Program at Kennedy Space Center gives it some unique advantages due to KSC facilities and location. The program also offers very positive potential benefits. However, to achieve the goal of the program--to improve the accuracy of lightning forecasting, thus increasing the launch window--the RTLP needs to overcome some very significant problems and shortcomings:

1. Lack of a coherent goal and the specific objectives leading there. Although I perceive the main goal of the RTLP as more flexibility in the launch criteria, with all subordinated projects leading to that goal, I have not been able to ascertain that upper KSC management has a specific goal in mind. It seems that objectives supporting the ultimate goal--things such as understanding the phenomena or developing a forecasting technique to improve thunderstorm and lightning forecasting--may be, and often have been, confused with the goal itself. Without a defined goal and a plan to achieve that goal, KSC will be doomed to flounder about, not knowing where it's going or how to get there.
2. Lack of top management support. As I perceive the situation, top KSC management does not really support the RTLP. Without that support and commitment, the program is doomed. Again, a program coordinator higher in the bureaucracy, reporting directly to top management, would enhance the RTLP.
3. Lack of adequate coordination among the diverse groups undertaking research essentially independently of each other. Each research group seems to place its own project above the total program. An example this year was the Airborne Field Mill Experiment (AFME), obviously supporting the RTLP. However, the AFME apparently enjoyed upper KSC management support and took precedence over the RTLP in allocation of resources, equipment, and personnel. To improve the RTLP, top KSC management must make a commitment to support the project. Further, program coordination should rest at a much higher level. The current coordinator is lower in rank than some of the supposedly subordinate research project leaders. Moreover, some project leaders of lower rank appear to have more influence on the RTLP than the coordinator does. There also appears to be some personal animosities.

4. Lack of cooperation. Along with coordination, cooperation among the groups does not exist, at least not as it should. Each group appears to hoard its data as if it were proprietary information, which it should not be. The individual research projects within the RTLP do not share data effectively, limiting the integration of diverse data sources into a unified forecasting method which should be the strength of the program at KSC. The potential benefit of having the RTLP at KSC is its unique data sources; lack of cooperation robs the program of its main virtue. Reorganizing program structure to place every individual research project under the RTLP, even when performed by an outside group, and demanding that every group share its results with all other groups, would improve cooperation. Last year, not one of the research groups involved in the RTLP sent me the data I requested; this year has thus far been no better.

Again let me stress that Kennedy Space Center not only offers the best location and climate for thunderstorm and lightning studies, it also offers unique and extremely valuable resources, capabilities, and expertise for conducting and managing such a research effort. Unfortunately, those assets have not yet been channeled into the cohesive, fully functioning program it could and should be. With a bit more management guidance and support, a firm goal and plan for achieving that goal, plus the required top management support, KSC could have a potent and dynamic rocket triggered lightning program. Any number of groups and individuals (including me) would be eager to contribute to the success of such a well designed and planned research effort.

IV

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ACRONYMS AND ABBREVIATIONS

- AFWAL - Air Force Wright Aeronautical Laboratories
- ASFL - Atmospheric Science Field Laboratory
Building near Mosquito Lagoon, about 15 miles north of the main KSC building complex, housing equipment, research space, and offices for conducting field experiments in lightning and other aspects of atmospheric science.
- D-WIPS - Digital Weather Image Processing System
A suite of electronics, computer, and four video monitors for acquiring and displaying radar, satellite, and conventional weather data in real time and as loops.
- EMP - Electromagnetic Pulse
Pulse of electromagnetic radiation emitted by nuclear explosions.
- ESMC - Eastern Space Missile Center
- FAA - Federal Aviation Administration
- ISIS - Integrated Storm Information System
System for storage and display of digital radar data and/or cloud-to-ground lightning strike location. Displays either radar or lightning data separately on the video terminal, or both together.
- KSC - Kennedy Space Center
- LIP - Lightning Location and Protection, Inc
Manufactures of ISIS.
- MSFC - Marshall Space Flight Center
- MIDDS - Meteorological Interactive Data Display System
World-wide weather data dissemination and display system capable of displaying radar, satellite, and conventional weather data in a variety of modes and combinations, including overlaying.
- NASA - National Aeronautics and Space Administration
- NRL - Naval Research Laboratories
- RTLP - Rocket Triggered Lightning Program
Program at KSC to launch small rockets into thunderstorm clouds, triggering lightning at the launch site.
- RTLS - Rocket Triggered Launch Site
Site on Mosquito Lagoon, near the ASFL, where RTLP personnel launch small rockets into active thunderstorm clouds. Contains launch sites over land and water.
- SUNYA - State University of New York at Albany